Demonstration Report

ESTCP Live Site Demonstrations Former Camp Beale

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Contents

Figures

Tables

Acronyms

Abbreviation	**Definition**
AOL	Advanced Ordnance Locator
APP	Accident Prevention Plan
BUD	Berkeley UXO Discriminator
DAQ	Data Acquisition System
EMI	Electro-Magnetic Induction
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
HASP	Health and Safety Plan
Hz	Hertz
IDA	Institute for Defense Analyses
IMU	Inertial Measurement Unit
ISO	Industry Standard Object
IVS	Instrument Verification Strip
LBNL	Lawrence Berkeley National Laboratory
MEC	Munitions and Explosives of Concern
MM	MetalMapper
MR	Munitions Response
Pd	Probability of Detection
Pfa	Probability of False Alarm
POC	Point of Contact
QA	Quality Assurance
QC	Quality Control
RTK	Real-Time Kinematic
ROC	Receiver Operating Characteristic
SERDP	Strategic Environmental Research and Development Program
SSHP	Site Safety and Health Plan
TEM	Time-domain Electro-Magnetic
TOI	Target of Interest
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance

1.0 INTRODUCTION

With support from the Environmental Security Technology Certification Program (ESTCP), Geometrics, Inc. (Geometrics) is commercializing an advanced electromagnetic induction (EMI) system for UXO detection and characterization. Called the MetalMapper, the new system draws elements of its design from advanced systems currently being developed by G&G Sciences, Inc. (supported by Naval Sea Systems Command, the Strategic Environmental Research and Development Program [SERDP], and ESTCP) and by the Lawrence Berkeley National Laboratory (LBNL) with support from SERDP and ESTCP.

CH2M HILL conducted a cued (i.e. static) MetalMapper classification survey between June 20 and 29, 2011, as part of the ESTCP Live Site Demonstrations at the former Camp Beale in Marysville, California. MetalMapper data were collected over 1,470 geophysical targets previously identified by EM61-MK2 data during an earlier phase of the Live Site Demonstrations.

The MetalMapper survey was conducted for ESTCP under contract W912HQ-11-C-0044, ESTCP Project Number MR-1063.

1.1 SURVEY OBJECTIVES

The overall objective of the MetalMapper demonstration was to accurately classify each of the targets as one of the following:

- Target of Interest (TOI), likely representing UXO;
- Non-TOI, likely representing another type of anomaly source such as UXO fragments, or piece of metallic clutter unrelated to UXO.

Additional objectives for this classification survey included the following:

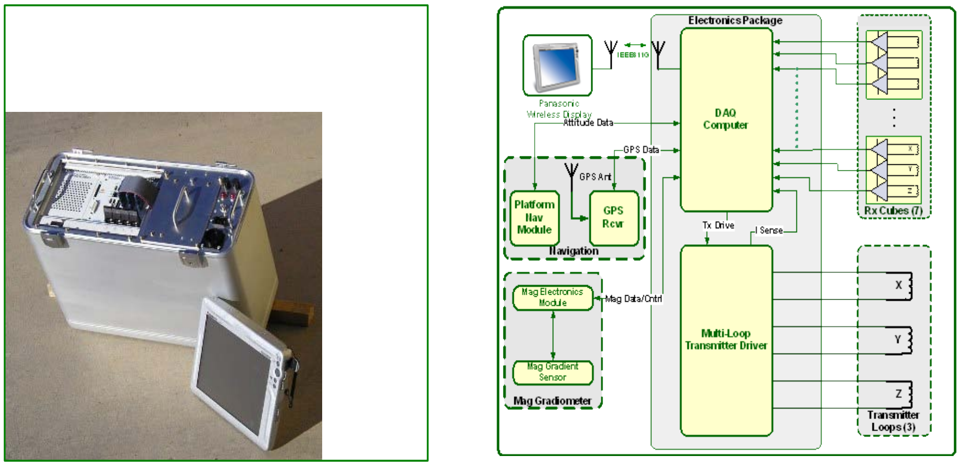
- Selecting a dig/no-dig threshold that recognizes all TOI (no false negatives/Type II error) while minimizing the number of false alarms (minimizing false positives/Type I error),
- Minimizing the number of targets classified as “can’t analyze”, and
- Estimating, correctly, target parameters such as polarizabilities, location, depth, and size.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

A block diagram of the data acquisition system (DAQ) system is shown in Figure 2-1. The MetalMapper system components include the following:

1. **Multiple Transmitter Loops**[1]: The MetalMapper antenna platform includes three mutually orthogonal transmitter loops.
2. **3-Axis Sensor Array**[2]: The MetalMapper antenna platform includes a spatial array of seven 3-axis receiver antennas (resulting in 21 independent measurements of the transient secondary magnetic field).



A) MM DAQ assembly with Panasonic terminal.

B) Function block diagram of MM system

Figure 2-1: The MetalMapper Data Acquisition System and a functional block diagram showing the major components of the overall system

3. **Electronically Switched Time Domain Electromagnetic Transmitter Loop Driver**: The transmitter can be controlled by the DAQ computer so that output can be directed to any single loop or automatically multiplexed between loops. Also, the fundamental waveform period, duty-cycle, and pulse polarity can be controlled. Typically, however, the loops are driven with a classical bipolar pulse-type time-domain electromagnetic (TEM) waveform (i.e., alternating pulse polarity with a 50% duty-cycle). Depending on the survey mode (e.g., static/dynamic), the fundamental frequency of transmission can be varied over the range $1.11 \leq f \leq 810$ hertz (Hz).

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[1] The 3 transmitter loops is a feature the MetalMapper has in common with the AOL2, LBNL BUD, and the USGS ALLTEM systems.

[2] The MM utilizes 3-axis receiver antennas, developed by G&G Sciences for the Navy's AOL system, to acquire measurements of the vector magnetic field. The antennas are small and approximate an observation of the field at a point.

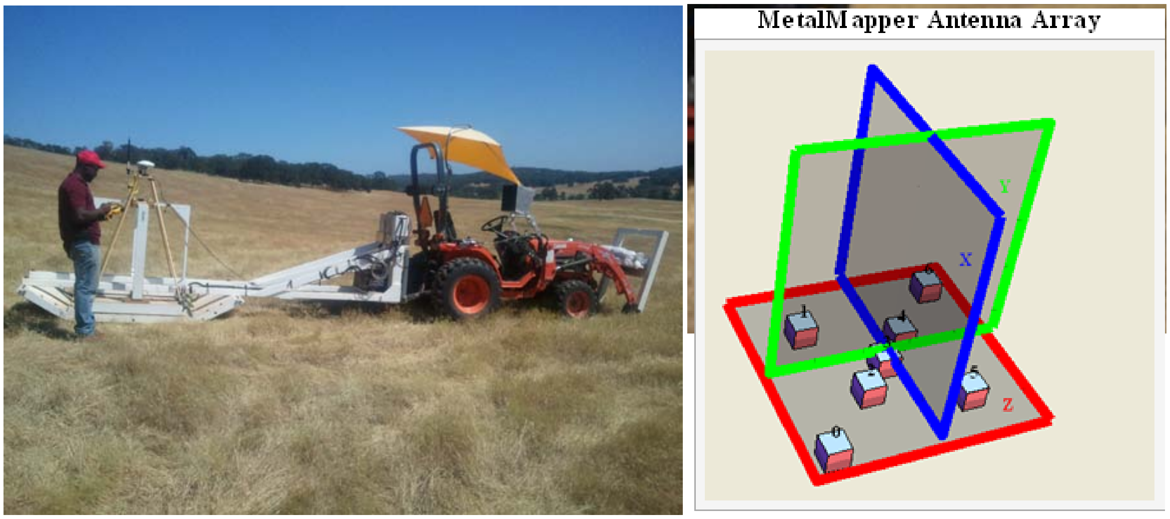

Figure 2-2: Photo showing the MetalMapper antenna array as it was deployed at Camp Beale. The side drawing illustrates the MetalMapper antenna array.

The antenna array is illustrated in the graphic on the right of Figure 2-2. It has three transmitter loops in the Z, Y, and X directions and contains seven tri-axial sensors located inside the Z (bottom) loop. At Camp Beale, the antenna array was towed behind a Kubota B7510 tractor. The antenna platform was positioned atop a sled that was dragged along the ground surface. Using the sled, the height of the antenna platform above the ground surface was 0.16 meters. It is possible to add wheels to the sled (not shown in Figure 2-2), although for the survey at Camp Beale, the sled was kept on the ground surface in order to minimize the height of the antenna platform above the geophysical targets.

The DAQ is built around a commercially available product from National Instruments. The DAQ, EM transmitter, and batteries for the entire system are packaged in an aluminum case that was secured atop the boom assembly during the survey at Camp Beale.

In addition to the components shown in Figure 2-1A, the instrumentation package includes a real-time kinematic global positioning system (RTK-GPS) receiver for recording positional data and inertial measurement unit (IMU) that records platform attitude (i.e. magnetic heading, pitch, and roll). These external devices are connected to the DAQ through serial RS232C ports. For the survey at Camp Beale, the RTK-GPS base station consisted of a Trimble R8 receiver and Trimble HPB450 external radio. CH2M HILL also utilized a Trimble R8 rover receiver with the MetalMapper system.

Additional information on the MetalMapper specifications, operational theory, and previous classification studies conducted under the direction of ESTCP can be found in the ESTCP Live Site Demonstrations Work Plan, MetalMapper at Former Camp Beale (CH2M HILL, 2011).

3.0 PERFORMANCE OBJECTIVES

The performance objectives for the MetalMapper classification survey and data analysis at Camp Beale site are summarized in Table 3-1.

Table 3-1: Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Maximize correct classification of targets of interest (TOI)	Number of TOI retained	• Prioritized anomaly lists • Ground truth/scoring provided by ESTCP/ IDA	Approach correctly classifies all TOI
Maximize correct classification of non-TOI	Number of false alarms eliminated	• Prioritized anomaly lists • Ground truth/scoring provided by ESTCP/ IDA	Reduction of false alarms by > 50% while retaining all TOI
Specification of no-dig threshold	Probability of correct classification and number of false alarms at demonstrator operating point.	• Demonstrator - specified threshold • Ground truth/scoring provided by ESTCP/ IDA	Reduction of false alarms by > 50% while retaining all TOI
Minimize number of anomalies that cannot be analyzed	Number of anomalies that must be classified as "Unable to Analyze"	Demonstrator target parameters	Reliable target parameters can be estimated for > 98% of anomalies on detection list
Correct estimation of target parameters	Accuracy of estimated target parameters	• Demonstrator target parameters • Results of intrusive investigation	X, Y < 15 cm (1σ) Z < 10 cm (1σ)

3.1 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

One of the two main objectives of this demonstration was to correctly classify all seeded items and any munitions and explosives of concern (MEC) items remaining at the site as TOI (i.e., identify true positives, with no false negatives).

3.1.1 Metric

The metric for this objective was the number of items on the MetalMapper anomaly list that were correctly classified as TOI.

3.1.2 Data Requirements

The requirement was that MetalMapper data were to be analyzed to create a prioritized dig list, which assigned each target to one of four categories: 0) Can't Extract Reliable Parameters; 1) Likely TOI; 2) Can't Decide; or 3) Likely Clutter.

The targets classified as either "Likely TOI" or "Can't Extract Reliable Parameters" were considered "Dig" targets. An additional number of "Can't Decide" targets down to a "Stop Dig Point" on the prioritized list were selected to be "Dig" targets and those below that point were considered "Don't Dig". Institute for Defense Analyses (IDA) personnel used their scoring algorithms to assess the results.

3.1.3 Success Criteria

The objective was to correctly classify all TOI on the prioritized anomaly list.

3.2 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

The second primary objective was to discriminate non-TOI from TOI and thereby maximize correct classification of non-TOI that could be eliminated from consideration during the intrusive investigation (i.e., identify true negatives, with minimal false positives.)

3.2.1 Metric

The metric for this objective was the number of targets on the ranked anomaly list correctly classified as non-TOI.

3.2.2 Data Requirements

The requirement was that MetalMapper data were to be analyzed to create a prioritized dig list, which assigned each target to one of four categories: 0) Can't Extract Reliable Parameters; 1) Likely TOI; 2) Can't Decide; or 3) Likely Clutter.

The targets classified as either "Likely TOI" or "Can't Extract Reliable Parameters" were considered "Dig" targets. An additional number of "Can't Decide" targets down to a "Stop Dig Point" on the prioritized list were selected to be "Dig" targets and those below that point were considered "Don't Dig". IDA personnel used their scoring algorithms to assess the results.

3.2.3 Success Criteria

The objective was to correctly label more than 50% of the non-TOI items as non-TOI while retaining all of the TOI above the dig threshold.

3.3 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

For the survey at the former Camp Beale, it is possible to tell the true capabilities of a classification procedure based solely on the final ranked anomaly list. However, all targets may not be dug for future investigations, so the success of the approach will depend on the ability of an analyst to accurately specify the dig/no-dig threshold.

3.3.1 Metric

The probability[3] of correct classification, P_{class}, and number of false alarms, N_{fa}, at the dig/no dig threshold in the prioritized dig list were the metrics for this objective.

3.3.2 Data Requirements

The requirement was that MetalMapper data were to be analyzed to create a prioritized dig list, which assigned each target to one of four categories: 0) Can't Extract Reliable Parameters, 1) Likely TOI, 2) Can’t Decide, or 3) Likely Clutter.

The category into which each target was placed was determined using a decision statistic developed during analysis of the MetalMapper data. The dig/no dig threshold for this project was the decision statistic value that separated targets classified as TOI from those classified as non-TOI (i.e., a value lying in the “Can’t Decide” range). IDA personnel used their scoring algorithms to assess the results.

3.3.3 Success Criteria

The objective was to correctly label more than 50% of the non-TOI items as non-TOI while retaining all of the TOI at the specified threshold.

3.4 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

Anomalies for which reliable parameters cannot be estimated using the collected MetalMapper data cannot be classified. These anomalies must be placed in the dig category, which reduces the effectiveness of the classification process.

3.4.1 Metric

The number of anomalies for which reliable parameters cannot be estimated was the metric for this objective.

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[3] It should be noted that when “probability” is referenced in this document, it is not a statistical probability, but rather a percent. The term is used to remain consistent with the work plans and scoring reports created under the SERCP/ESTCP program.

3.4.2 Data Requirements

The requirement was that those targets for which parameters were not reliably estimated were to be identified as such on the prioritized dig list submitted following analysis of the MetalMapper data.

3.4.3 Success Criteria

The objective was to estimate reliable parameters for > 98% of the targets on the prioritized dig list.

3.5 OBJECTIVE: CORRECT ESTIMATION OF TARGET PARAMETERS

This objective involves the accuracy of the target parameters that were estimated in the first phase of the analysis. Successful classification was only possible if the input features were internally consistent. The clearest way to satisfy this condition was to estimate the various target parameters accurately.

3.5.1 Metric

Accuracy of estimation of target parameters was the metric for this objective.

3.5.2 Data Requirements

The requirement was that target parameters were to be provided as part of the final results submittal. IDA analysts compared these estimated parameters to those measured during the intrusive investigation and determined via subsequent in-air measurements.

3.5.3 Success Criteria

The objective was to estimate X, Y locations within 15 cm (1σ) and the estimated depths within 10 cm (1σ), of the true location.

4.0 SITE DESCRIPTION

The MetalMapper survey was conducted in two areas at the former Camp Beale. One area was utilized for only MetalMapper surveying and the other was utilized as a combined survey area. The combined area was surveyed using MetalMapper as well as the other advanced classification systems evaluated as part of the ESTCP Live Site Demonstration at the former Camp Beale.

The MetalMapper-only survey area consisted of 22 contiguous 30-meter by 30-meter grids. A total of 1,213 geophysical targets were surveyed with the MetalMapper in this area. The survey area was predominately grass covered with moderately steep slopes along the northeastern edge of the survey area. The site was relatively open and contained a minimal number of rock outcrops. The combined survey area consisted of 4 contiguous 30-meter by 30-meter grids. A total of 257 geophysical targets were surveyed with the MetalMapper in this area. It was relatively open, grass covered, moderately to steeply-sloped and contained a minimal number of rock outcrops. The survey areas at the former Camp Beale were selected by the ESTCP Program Office. Survey benchmarks for RTK-GPS base station locations had also been established by the ESTCP Program Office during earlier phases of the Live Site Demonstration.

Suspected munitions within the survey areas at the former Camp Beale include, but may not be limited to, the following: 37 mm projectiles, 60 mm mortars, 81 mm mortars, and 105 mm projectiles.

Additional information on the site history, description, survey areas, and site selection criteria can be found in the ESTCP Live Site Demonstrations Plan (ESTCP, 2011).

5.0 SURVEY EXECUTION

5.1 SITE PREPARATION

The survey areas were prepared by ESTCP in advance of the MetalMapper survey, so no special site preparation activities (e.g. vegetation removal, grass cutting, etc.) were necessary at the start of the MetalMapper survey. Vinyl-stem flags marked the locations of the geophysical targets in the combined survey grids because several of the other advanced classification systems evaluated at former Camp Beale do not have real-time GPS positioning capabilities like the MetalMapper. No flags were located within the MetalMapper-only grids.

An instrument verification strip (IVS) was constructed by ESTCP during an earlier phase of the Live Site Demonstration at former Camp Beale. Items buried within the IVS included the following: steel sphere, 105-HEAT, 37 mm projectile, 60 mm mortar and a small industry standard object (ISO). Information on burial depth, orientation and geographic coordinates of the IVS items can be found in the ESTCP Live Site Demonstrations Plan (ESTCP, 2011).

5.2 ON-SITE TRAINING

On-site training on the MetalMapper operation was provided to CH2M HILL by Geometrics personnel on June 20, 2011. On-site data analysis training was provided by Snyder Geoscience, Inc. between June 21 and 23, 2011.

5.3 CALIBRATION AND SYSTEM FUNCTIONAL CHECKS

Daily calibration and system functional checks were performed as part of routine quality assurance/quality control (QA/QC) procedures. These checks were performed at or near the IVS location.

Twice daily measurements of the IVS were made with the MetalMapper. These data were provided each day to the onsite CH2M HILL analyst and were used to evaluate the stability of the MetalMapper system over the duration of the survey as well as the response over specific, known items. In addition, measurements along the IVS were recorded in order to evaluate the accuracy of the RTK-GPS positional data throughout the duration of the survey.

Twice daily measurements over an established background location near the IVS were also recorded as part of the daily system functional checks. This location was a shallow test pit that had been excavated under the direction of ESTCP and determined to be relatively free of subsurface metal. These data were used to evaluate the system response at a consistent location relatively free of subsurface metal throughout the duration of the survey.

Calibration data collected at former Camp Beale included a series of measurements over inert items placed in the test pit. The items, burial depth, and orientation are provided in Table 5-1. These measurements were used primarily as training data and to develop a target classification library to be used during data analysis.

Table 5-1: Calibration Measurements in Test Pit

Item	Depth (cm)	Orientation
Empty pit (static - 5 min)	N/A	N/A
Steel sphere	25	N/A
37 mm projectile	10, 20	Horizontal (along track and across track), 45° down, 90° down
60 mm mortar	20, 30	Horizontal (along track and across track), 45° down, 90° down
81 mm mortar	25, 40	Horizontal (along track and across track), 45° down, 90° down
105 mm projectile	30, 45	Horizontal (along track and across track), 45° down, 90° down

5.4 DATA COLLECTION PROCEDURES

The acquisition parameters utilized for the survey at former Camp Beale are presented in Table 5-2. The parameters were established based on experience during previous MetalMapper demonstration surveys. The CH2M HILL data collection team consisted of two on-site staff. Field work was performed in accordance with the Accident Prevention Plan (APP) and Site Specific Health and Safety Plan (SSHP) (CH2M HILL, 2011).

Table 5-2: Acquisition Parameters

Mode	Tx Mode	Hold-Off Time (µs)	Block Period (s)	Rep Fctr	Dec Fctr (%)	Stk Const	Base Freq (Hz)	Decay Time (us)	No. Gates	Sample Period (s)	Sample Rate (S/s)
Static	ZYX	50	0.9	27	10	10	30	8333	50	9	N/A

<u>Definitions:</u>
Tx Mode: Transmitter mode. ZYX = All three transmitters active
Hold-Off Time: Relates to calculating gates; the 50µs hold-off means that the 2nd gate starts no earlier than 50µs. Gates are calculated starting with the delay time of the last sample. The last gate (50th) has a width of 8333.33 x 0.1µs calculated to the nearest sample integer sample interval of 4µs.
Block Period: Data are acquired during a specified time period (in seconds) called a block period.
Rep Fctr: The number of transmitter periods per block period. The repetition factor will always be a power of 3 (e.g., 1,3,9,27,…)
Dec Fctr: Decimation Factor; a decimal fraction or percentage used to calculate the gate widths as a function of delay time to the end of the time gate under construction. Width = Dec Fctr * Gate End Time. The Width is rounded to an integer number of ADC sample intervals (4 us).
Base Freq: Base Frequency; this is the fundamental frequency of the transmitter waveform. Base Frequency= Rep Factor/Block Time (e.g. 27/0.9 = 30Hz)
No. Gates: Number of gates; gate widths and center times are calculated starting with the sample with the longest delay time using the decimation factor to figure out the gate width. The process proceeds from late to early gates and stops when the start of the next gate is less than the delay time. There is always one more gate (the 1st gate) than the aforementioned procedure allows. The first gate is used for a composite gate (i.e., an average of several gates). The parameters of that gate are contained in the AcqParams block of the TEM data file. It is not used for static data interpretation.
Sample Period: The Block Time * Stk Constant.

5.4.1 Production Survey

MetalMapper data acquisition was performed over 1,470 targets. The geophysical target locations were provided by ESTCP prior to the start of the MetalMapper survey. Seed item locations were included in the target list, their locations known only to ESTCP. The target list was formatted for input into the MetalMapper data acquisition software EM3DAcquire, developed by G&G Sciences, Inc.

The acquisition software displays a map of the target locations with their assigned unique IDs, where after a target is recorded, the software displays an "X" on top of the target location, thus enabling the operator to know which points have been collected. Each day, the complete list of points recorded to-date was loaded on to the map to avoid unnecessary recollection of targets. The software also provided a real-time display of the GPS quality parameters and the IMU readings, where potential problems with these data streams could be identified before taking a measurement.

With the acquisition parameters in Table 5-2, the length of time to record a single target location was approximately 30 seconds.

5.4.2 Background Acquisition

Periodic background readings were taken in static mode with the MetalMapper each day during data collection. Background readings were taken approximately every 60 to 90 minutes and were intended to evaluate spatial changes in background conditions across the survey area as well as to evaluate whether background levels changed over time as a result of decreased battery voltage or sensor heating during the course of each day in the field.

The background locations were identified in real-time using the MetalMapper EM3DAcquire acquisition software. The software facilitates the identification of suitable background locations by providing a real-time graphical display of sensor response amplitude and position relative to nearby metallic targets. Suitable background locations were those where amplitudes appeared to be minimal and where there did not appear to be nearby metallic sources.

5.4.3 Data Quality Checks

In addition to the aforementioned calibration and system functional checks, qualitative checks of the data were performed using the plot functions of the EM3DAcquire acquisition software. The transmitter output current and 21 receiver measurements were periodically generated for the raw survey data in order to identify potential system malfunctions.

A final check on the quality of static data was completed during preliminary analysis with the program MM/RMP. This final check was generally performed within 24 hours of data collection, and if necessary, targets identified for re-collection were provided to the field team. For the survey at the former Camp Beale, a total of 110 targets were identified for re-collection.

Re-collection was typically a result of the lateral offset of the preliminary modeled target location falling outside the established positional tolerance from the center of the MetalMapper array. High fidelity estimates of a target's principal polarizability curves depend on adequate illumination of the target along each of its principal axes. A conservative guideline is that targets with horizontal offsets of 40 cm or more from the center of the Z transmitter were not adequately illuminated and thus their symmetry properties (i.e., one major polarizability curve over two nearly identical minor polarizability curves) may not be apparent. For the survey at the former Camp Beale, the positional tolerance was therefore established at 40 cm.

Additional reasons for re-collection also included, to a lesser extent, poor GPS data quality of the recorded target location or weak signal response due to site conditions (e.g. rock outcrop at target location) or the potential impact from multiple targets located within the array platform footprint.

5.4.4 Data Handling

Data were recorded in binary format to the hard disk of the MetalMapper DAQ. Raw data files were downloaded daily and transmitted to the project analyst along with relevant field notes. Raw and pre-processed data were provided to ESTCP upon completion of the survey. Raw, pre-processed, and final processed data are kept on file at CH2M HILL.

The file prefix nomenclature utilized at the former Camp Beale survey areas was as follows: T=target location; X=daily IVS measurement; B=periodic background reading; PIT=test pit measurement. This nomenclature was used because the acquisition software stores file names in sequential order. The unique target ID provided by ESTCP is embedded within the data file, although this ID is not reflected in the actual file name. At the request of ESTCP, the unique IDs for targets requiring re-collection were increased by 10,000 (e.g. recollected target ID 1202 would be saved as target 11202).

5.5 VALIDATION

At the conclusion of data collection activities, all geophysical targets were excavated by ESTCP. Each item was identified, photographed, its depth measured, its position recorded using RTK-GPS, and the item was removed, if possible. All non-hazardous items were saved by ESTCP for later in-air measurements. This ground truth information was provided by ESTCP and was used to further validate the performance objectives listed in Section 3.0.

6.0 DATA ANALYSIS

Analysis and interpretation of the MetalMapper data collected at the former Camp Beale involved the following steps: pre-processing, parameter estimation, analysis of training data, and classification.

6.1 PRE-PROCESSING

Collected data were preprocessed using the MM/RMP software package. MM/RMP was used to convert the recorded geographic coordinates to Universal Transverse Mercator (UTM) coordinates (Zone 10 North), correct the survey location point using attitude data from the IMU and remove the background field from the receiver transients. Pre-processed data for each target were exported as a .CSV file. CH2M HILL imported preprocessed data into Geosoft's Oasis Montaj processing environment for further analysis.

6.2 PARAMETER ESTIMATION

Parameter estimation was performed using the UX-Analyze module in Oasis Montaj. Target data were inverted using both single-source and multi-source dipole response models to estimate target parameters. The principle parameters of interest for use in classification of the targets were the three polarizabilities (β_1, β_2, and β_3) estimated for each target by UX-Analyze. In addition to estimates for the three βs for each target, an estimated location and depth was also returned by UX-Analyze for each target during inversion. Targets modeled outside the positional tolerance of 40 cm from the center of the MetalMapper array were identified for re-collection (see Section 5.4.3).

While not used extensively in a classification survey where all geophysical targets are intrusively investigated, the location and depth are significant when considering their effects on the success of an intrusive investigation based on MetalMapper results. The same is true for inclination, depth, and rotation of the source object, which are also estimated by UX-Analyze. For the analysis of the former Camp Beale data, these parameters were evaluated, although they were not a metric for the survey performance objectives.

6.3 ANALYSIS OF TRAINING DATA

Training data included data that was collected during previous ESTCP MetalMapper surveys as well as the test pit data collected by CH2M HILL described in Section 5.3. These data were used to create a library of polarizabilities for various standard munitions types. CH2M HILL elected to include additional munitions types not known to have been used at Camp Beale in the library of polarizabilities. This decision was based primarily on the ESTCP Munitions Response Live Site Demonstrations Plan, Section 4.3, (ESTCP, 2011), which states that the suspected munitions in this demonstration area include, but are not limited to 37 mm projectiles, 60mm mortars, 81mm mortars and 105mm projectiles, but that due to the complex history of the site and overlapping network of historical ranges, it is also likely that other munitions types beyond those listed above may be encountered. As a result, CH2M HILL elected to include the following additional items in the library:

- 155mm projectiles
- 2.36in rockets (intact, tail booms, and rocket motors)
- 2.75in rockets
- 20mm projectiles
- 25mm projectiles
- 3in Stokes mortar projectiles
- 4.2in mortar projectiles
- 40mm projectiles
- 57mm projectiles
- 75mm projectiles
- 76mm projectiles
- BDU-28s
- BDU-33s
- M42 bomblet
- M48 fuzes
- MK 118 Rockeyes
- MK23 practice bomb
- MK II grenades
- Small ISOs (included because were used in IVS)

The library of polarizabilities was compared to the recovered MetalMapper target polarizabilities from Camp Beale for classification purposes. At the request of CH2M HILL, additional training data were provided by ESTCP for 49 geophysical targets for use during the classification process.

6.4 CLASSIFICATION

The classifier used to create the ranked dig list for the former Camp Beale targets was based primarily on the confidence metric generated by UX-Analyze during a comparison of the β values estimated for each surveyed target and the β values in the munitions library developed for the project. The confidence metric indicates the fit ratio between a target and the items in the library, with higher metrics indicating a better fit between the target and the corresponding item in the library. Targets with a confidence metric of 0.80 or better are typically considered a good fit to the library item.

Comparison of target data to the library was performed using the Advanced Target Classification function of UX-Analyze, which allows the user to weight the importance of each of the three polarizability curves for the purposes of the comparison. The first comparison performed weighted all three polarizabilities equally. Following this initial comparison, all relatively high confidence metrics generated were considered indicative of TOI. Preliminary classification was based on a fit ratio of 0.80 as the cut-off between targets likely to be TOI and targets identified as either non-TOI or those for which an initial decision could not be made. This initial classification was then refined as described below.

Targets with high fit ratios (greater than 0.80) to library items using all three polarizabilities were classified as Category 1 (dig on first pass) targets. Their position on the ranked dig list was determined in reverse order of confidence metric (i.e. higher confidence metrics are of higher priority on the list). Targets with the same confidence metrics were ranked according to the response amplitude from the EM61-MK2 data, with higher amplitude anomalies given priority over lower amplitude anomalies.

Lower confidence metrics could be indicative of either non-TOI sources or of poor quality MetalMapper data due to low signal-to-noise or the inability to position the MetalMapper sensor array directly over the target location (e.g. due to obstacles such as rock outcrops). Two additional categories were identified using the first comparison of MetalMapper data to library data: 1) targets for which a decision cannot be made, and 2) targets likely to be non-TOI. The threshold separating these two classes was initially set at a confidence metric of 0.60. Targets were repositioned on the dig list based on further individual analysis, as described below.

Following initial categorization, the target to library polarization curve matches for all targets not assigned to Category 1 were examined by the analyst. The goal of this examination was to identify targets for which poor MetalMapper data quality, despite the effort to recollect questionable data, was the potential cause for a lower confidence metric rather than simply a poor match due to a non-TOI source. Targets showing poor polarizability fits were noted for further analysis if any of the three polarization curves appeared to be of sufficient quality that it/they could be used for comparison to the library data. If none of the three curves appeared useful, the target was classified as Category 0 (cannot analyze) and was added to the top of the ranked dig list.

Targets for which one or two polarization curves appeared useful were compared to the library a second time, with the β(s) exhibiting poor data quality removed from the comparison (i.e. it/they were given 0 weights). The targets involved in the reanalysis were re-categorized and re-ranked on the dig list based on the revised confidence metrics. The confidence metric thresholds used to differentiate likely TOI from likely clutter were different for one or two curve comparisons than those used for three curve comparisons. These thresholds were evaluated following one- or two-curve analysis. Following completion of the various comparisons of targets data to the library data, a dig/no dig threshold was identified on the dig list. The threshold was within Category 2, those targets for which a TOI/non-TOI decision was not able to be made.

The initial ranked dig list was submitted for comparison to the results of the intrusive investigation. In accordance with the ESTCP Live Site Demonstrations Plan (ESTCP, 2011), the results of the intrusive investigation for those targets classified as “dig” on the ranked dig list were supplied following submittal of the list to allow the demonstrator to analyze the results and revise the dig/no dig threshold and/or ranking of each target. CH2M HILL did not revise the initial dig list following this analysis but elected to use the same rankings for the final ranked dig list submitted to ESTCP for scoring.

6.5 DELIVERABLES

The following deliverables resulted from the data collection at Camp Beale:

1) **Final Prioritized Dig List:** Detailed in Section 6.4.
2) **Cued Data:** Text readable cued data files were provided in 2 forms: a) raw data, and b) pre-processed data. The following operations were performed on the pre-processed cued data files:
    i) **Coordinate Conversion:** GPS lat/lon was converted to UTM Zone 10N, NAD83 coordinates.
    ii) **Coordinate Corrections:** Using cart attitude angles (heading, pitch, and roll) the UTM coordinates was corrected to MM platform reference point.
    iii) **Background Removal:** An appropriate background was removed from all the receiver transients. Thus, the transients written to the file were estimates of the secondary fields after background had been removed.
3) **Cross-Reference List**: A text readable table that associates MM filenames with each Target ID.

7.0 PERFORMANCE ASSESSMENT

The performance objectives for this classification survey and the corresponding results are summarized in Table 7-1. Details on the results for each objective are subsequently discussed in the following sections.

Table 7-1: MetalMapper Survey Results for Former Camp Beale

Performance Objective	Metric	Data Required	Success Criteria	Objective Met?
Maximize correct classification of targets of interest (TOI)	Number of TOI retained.	Prioritized anomaly lists	Approach correctly classifies all TOI	No
Maximize correct classification of non-TOI	Number of false alarms eliminated.	Prioritized anomaly lists	Reduction of false alarms by > 50% while retaining all TOI	No
Specification of no-dig threshold	Probability of correct classification and number of false alarms at demonstrator operating point.	Demonstrator - specified threshold	Reduction of false alarms by > 50% while retaining all TOI	No
Minimize number of anomalies that cannot be analyzed	Number of anomalies that must be classified as "Unable to Analyze."	Demonstrator target parameters	Reliable target parameters can be estimated for > 98% of anomalies detection list.	No
Correct estimation of target parameters	Accuracy of estimated target parameters.	• Demonstrator target parameters • Results of intrusive investigation	X, Y < 15 cm (1σ) Z < 10 cm (1σ)	No

7.1 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

One of the two main objectives of this demonstration was to correctly classify all seeded items and any MEC items remaining at the site as TOI (i.e., identify true positives, with no false negatives).

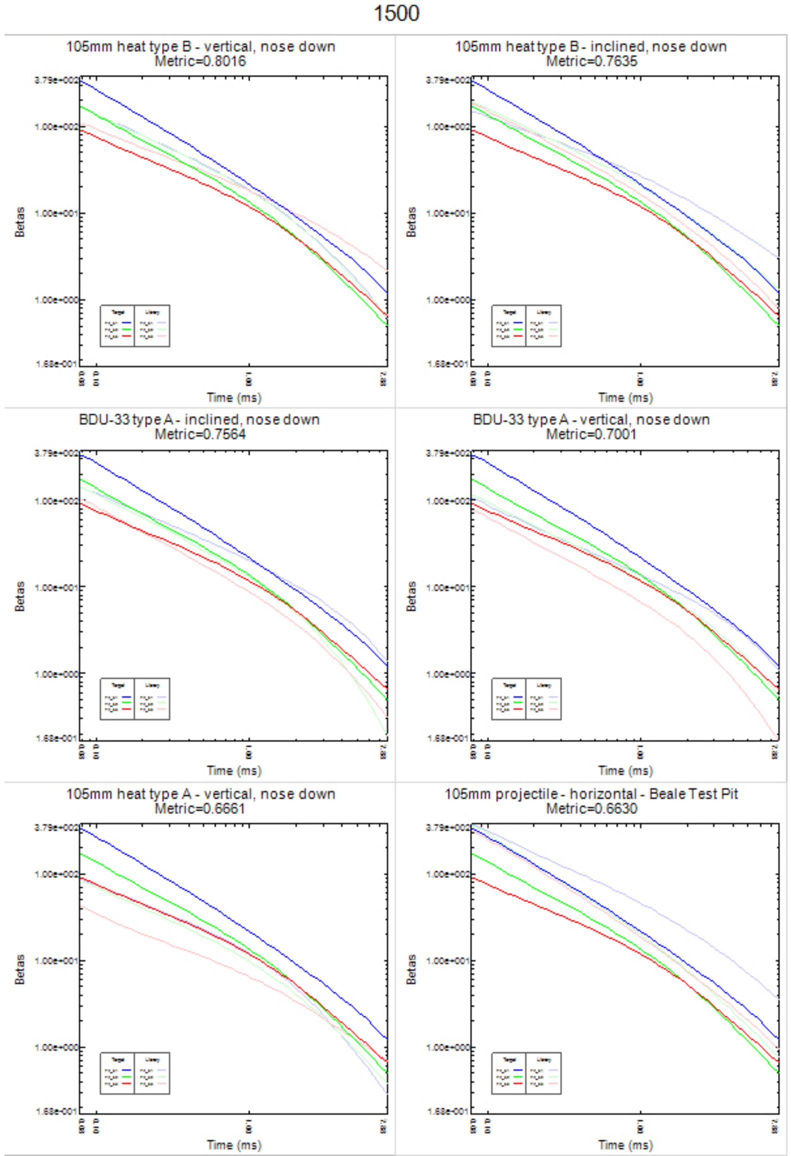
The cued MetalMapper survey and subsequent data analysis and classification failed to identify all TOI, and thus the performance objective was not met. Seven TOI were not identified for excavation: three small ISOs, two 37mm projectiles, and two 105mm projectiles. The inverted data of these missed TOI did not appear to match well with any ordnance items, and they were therefore classified as non-TOI.

The missed TOI are discussed in the following subsections.

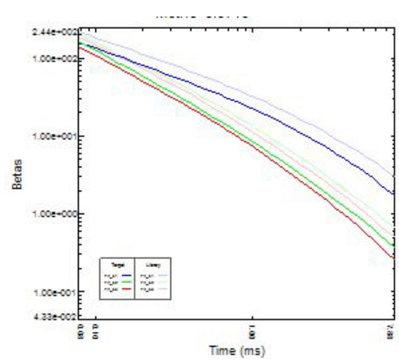
7.1.1 Target BE-1500 – 105mm projectile

Although UX-Analyze returned a 0.8016 confidence metric match between target BE-1500 and a 105mm projectile, the polarizability curves did not visually match those of a typical 105mm projectile (Figure 7-1, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors). The recovered primary β decayed more quickly than the corresponding β of previously seen 105mm projectiles, and the recovered minor βs roughly paralleled the primary beta throughout the decay curve rather than falling off at a quicker rate as seen in typical 105mm projectiles. Target BE-1500 was therefore classified as a non-TOI.

Figure 7-1: Target BE-1500 Classification Results



Closest Library Matches for Target BE-1500

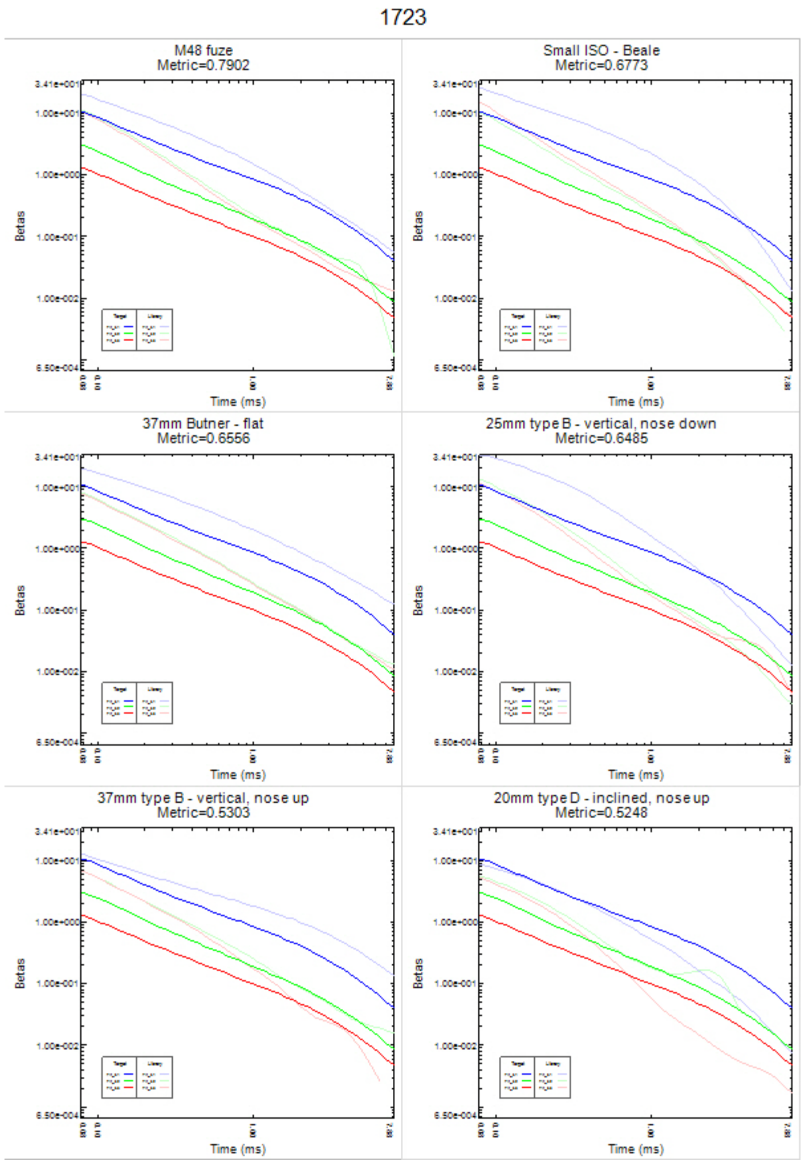


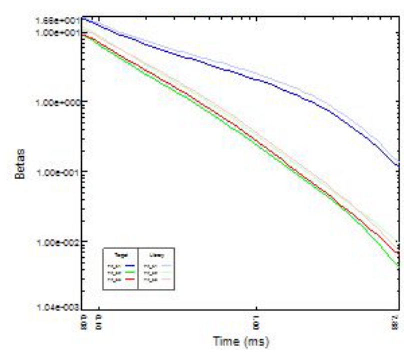
Typical 105mm Projectile βs

7.1.2 Target BE-1723 – 37mm projectile

As with Target BE-1500, the recovered polarizability curves of target BE-1723 did not visually match those of a typical 37mm projectile (Figure 7-2, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors). The amplitude of the recovered primary β appeared lower than that typically seen in 37mm projectiles, and the recovered minor βs roughly paralleled the primary beta throughout the decay curve rather than falling off at a quicker rate as seen in typical 37mm projectiles. Target BE-1723 was therefore classified as a non-TOI.

Figure 7-2: Target BE-1723 Classification Results





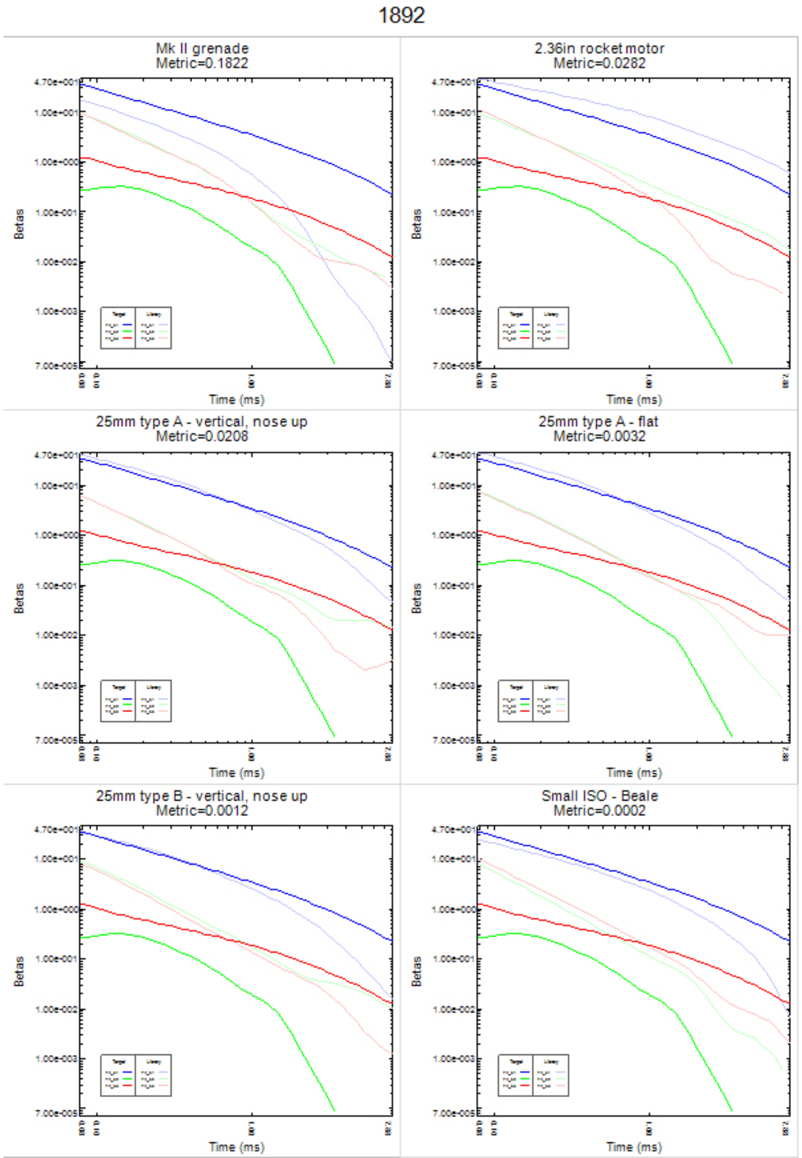
Closest Library Matches for Target BE-1723

Typical 37mm Projectile βs

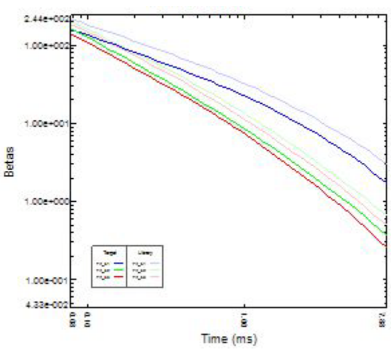
7.1.3 Target BE-1892 – 105mm projectile

The recovered polarizabilities of target BE-1892 do not appear to match those of a 105mm projectile or any other common ordnance item (Figure 7-3, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors). The shape of the recovered primary β matches fairly well with the expected primary β shape of a 105mm projectile, but the amplitude is much lower than that seen in typical 105mm projectiles. The secondary and tertiary βs bare no resemblance to those of a 105mm projectile. The classification library used in this analysis contained numerous ordnance items in addition to those items expected at the site (37mm projectiles, 60mm mortars, 81mm mortars and 105mm projectiles) and therefore returned a correspondingly large number of fit matches. In order to filter the returned data to a manageable quantity, the analyst reviewed only the top six matches for each target. The fit between target BE-1892 and a 105mm projectile from the library was not good enough to be displayed as one of the top six matches, and the vague similarity that did exist was therefore not apparent.

Figure 7-3: Target BE-1892 Classification Results



Closest Library Matches for Target BE-1892

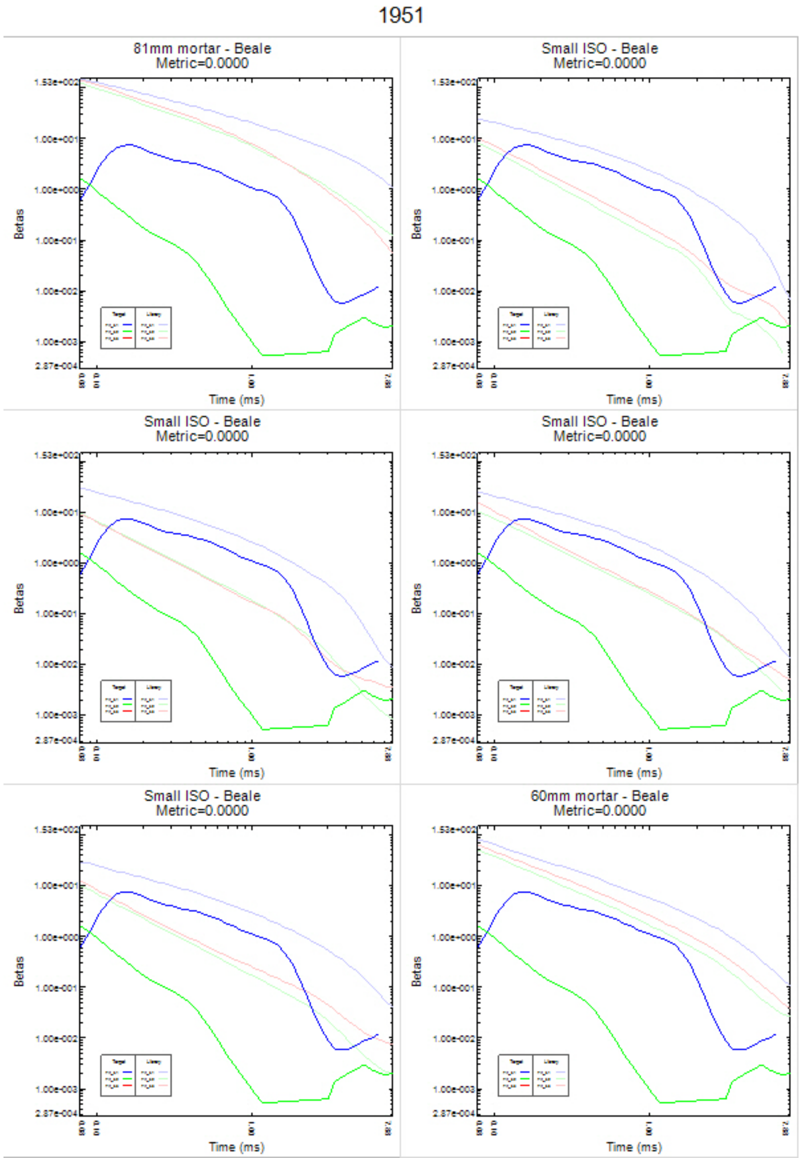


Typical 105mm Projectile βs

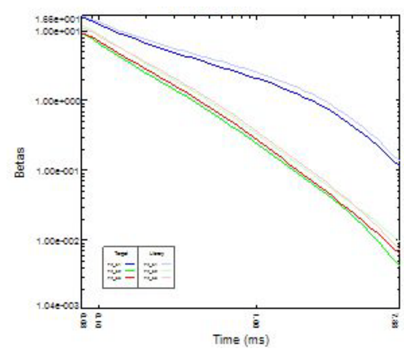
7.1.4 Target BE-1951 – 37mm projectile

Target BE-1951, a 37mm projectile, could have been identified as a target without data of sufficient quality to be properly analyzed. The two recovered polarizabilities (Figure 7-4, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors) are likely not strong enough for confident classification but due to their dissimilarity to any typical ordnance item were incorrectly classified as non-TOI.

Figure 7-4: Target BE-1951 Classification Results



Closest Library Matches for Target BE-1951

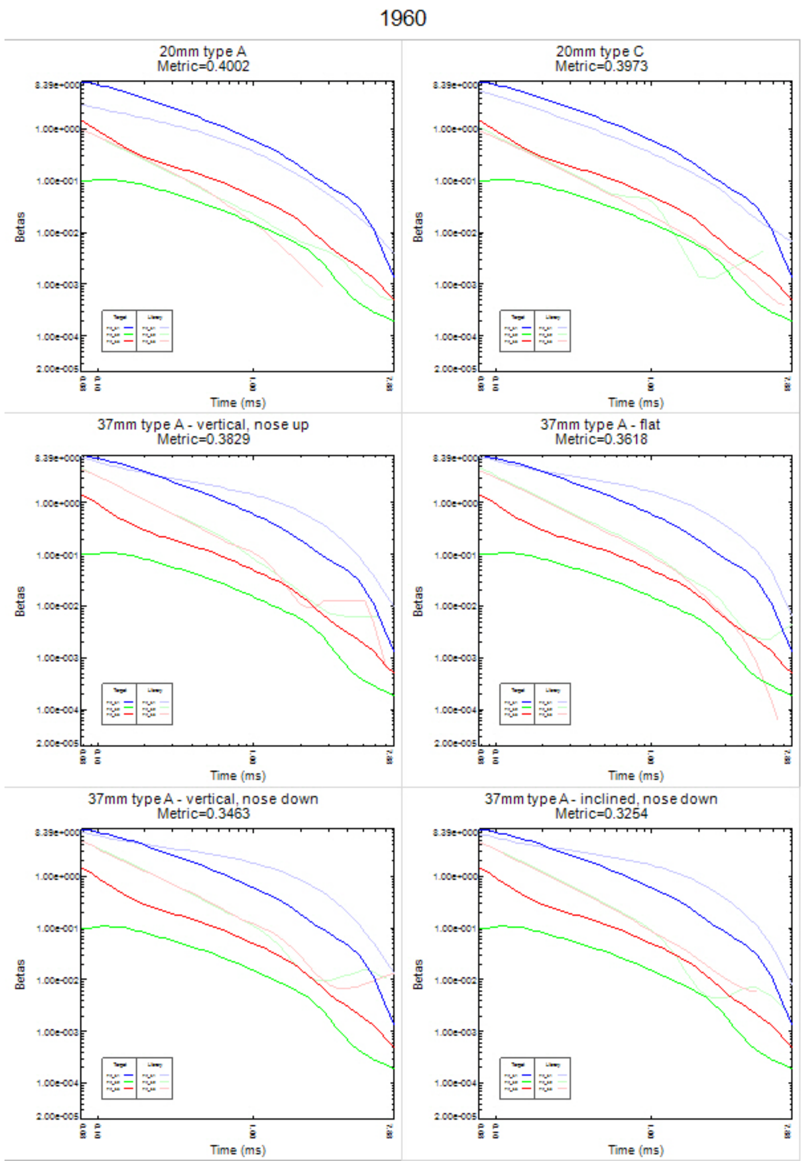


Typical 37mm Projectile βs

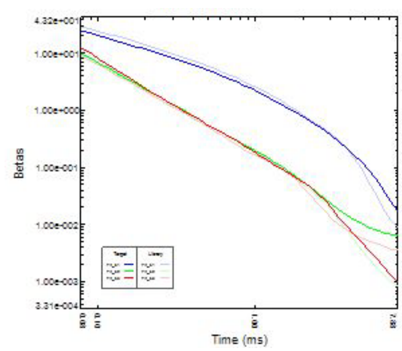
7.1.5 Target BE-1960 – small ISO

As with target BE-1892, the failure to identify target BE-1960 as a small ISO is due, in part, to a classification library that includes ordnance items not found at Camp Beale. The two best matches of the recovered polarizabilities (Figure 7-5, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors) were with 20mm projectiles, which were not found at the site. The remainder of the six viewed matches were with 37mm projectiles, and no matches with small ISOs were returned. The shape of the primary β does mimic the expected shape of a small ISO's primary β, but the amplitude is considerably lower than that of a typical small ISO. The low amplitude of the βs coupled with the lack of symmetry displayed in the minor βs caused the match to a small ISO to fall out of the top six displayed library matches, and thus, the vague similarity was not apparent.

Figure 7-5: Target BE-1960 Classification Results



Closest Library Matches for Target BE-1960

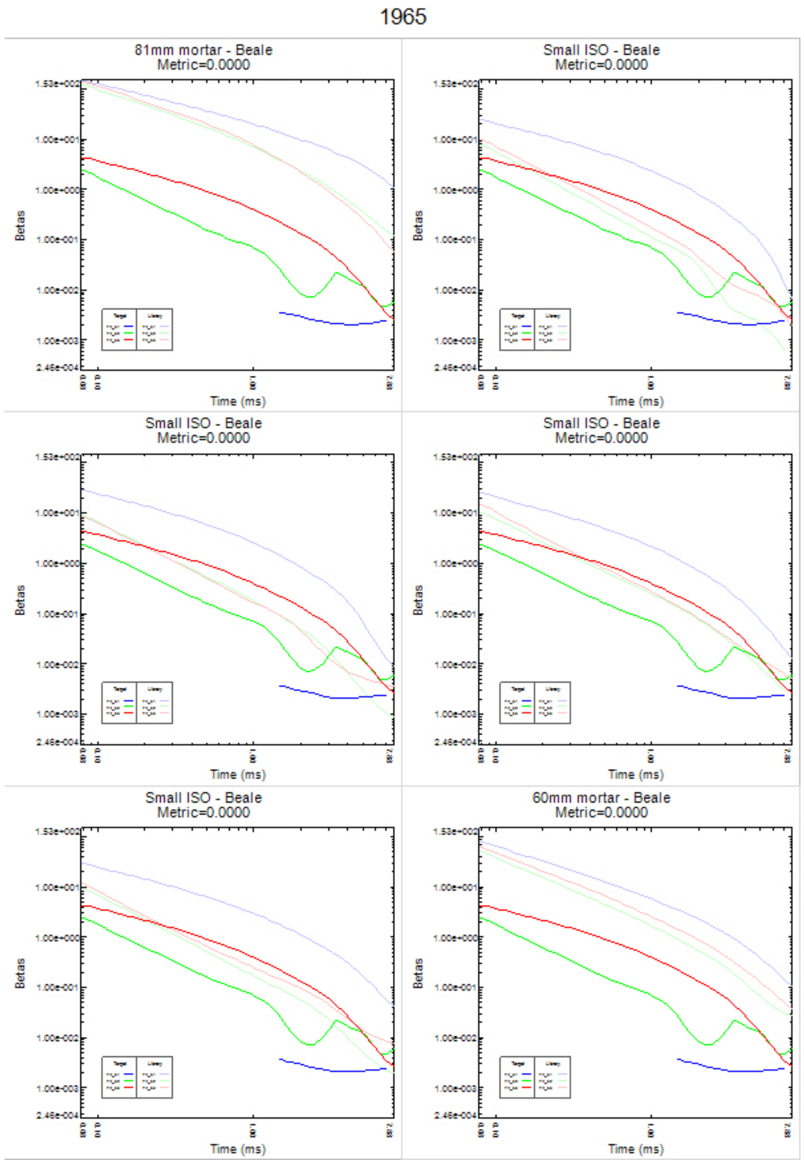


Typical small ISO βs

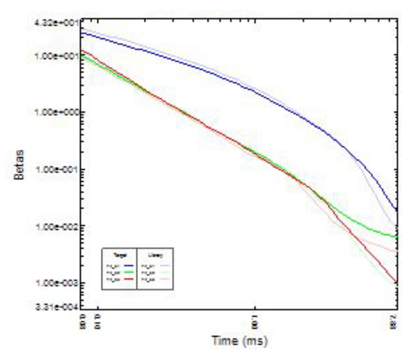
7.1.6 Target BE-1965 – small ISO

The recovered primary polarizability of target BE-1965, and to a lesser extent the recovered secondary β (Figure 7-6, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors) match the expected β shapes of a small ISO very well, but the amplitudes are considerably smaller, which typically indicates a smaller item. The low amplitudes of the βs resulted in this target being classified as a non-TOI.

Figure 7-6: Target BE-1965 Classification Results



Closest Library Matches for Target BE-1965

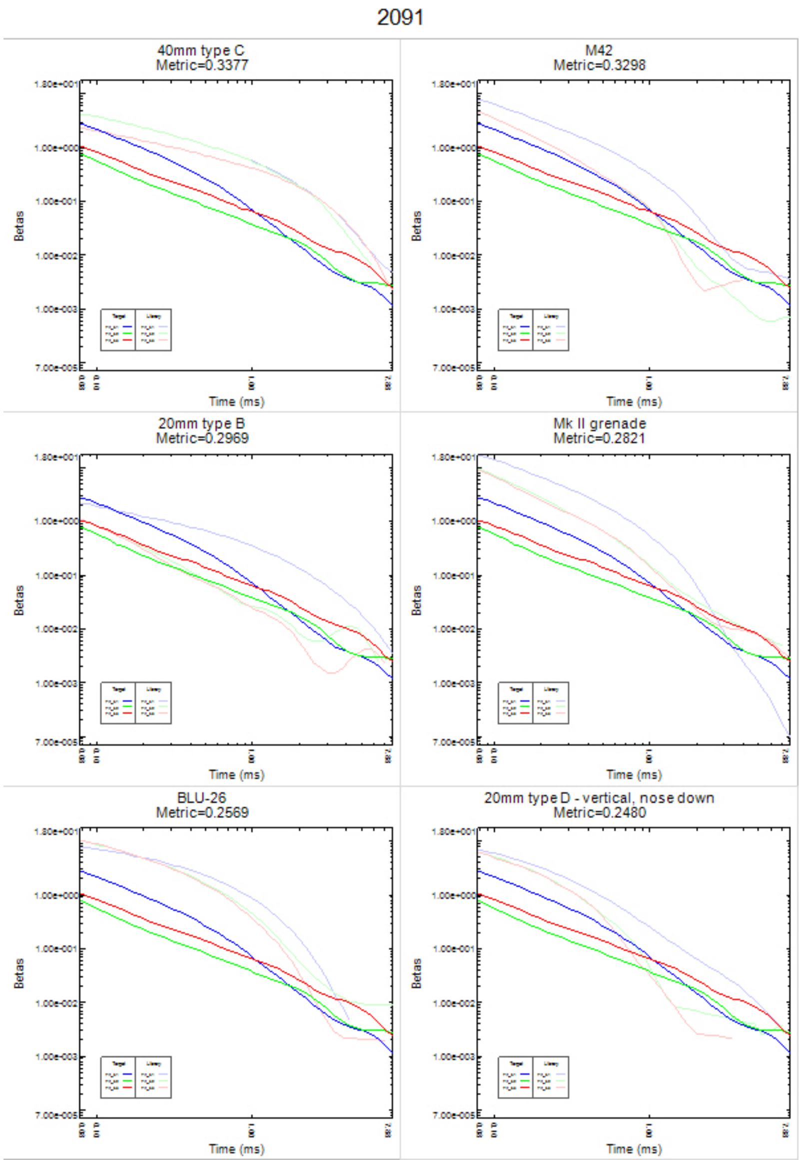


Typical small ISO βs

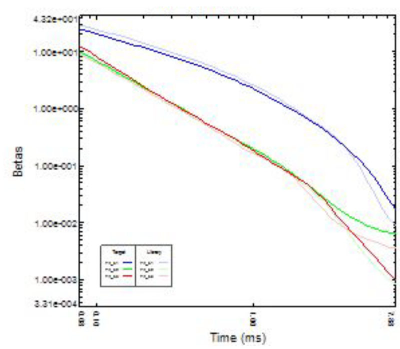
7.1.7 Target BE-2091 – small ISO

The recovered polarizabilities of target BE-2091 (Figure 7-7, with the recovered βs in bold colors, and the βs of the closest library matches in faded colors), a small ISO, do not provide a good match with an ISO or any typical ordnance item. Neither the amplitude nor the shape of the βs, match well, and the target was therefore classified as a non-TOI.

Figure 7-7: Target BE-2091 Classification Results



Closest Library Matches for Target BE-2091



Typical small ISO βs

7.2 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

This was the second of the two primary measures of the effectiveness of the classification survey. In addition to correctly classifying TOI, the effectiveness of the MetalMapper in discriminating munitions is a function of the degree to which responses that do not correspond to TOI can be eliminated from consideration during the intrusive investigation (i.e., the ability to identify true negatives, with minimal false positives).

This performance objective was not met since not all TOI were retained above the dig threshold; however, 81% of the non-TOI items were correctly labeled. The objective was to be considered met if more than 50% of the non-TOI items were correctly labeled as non-TOI while retaining all of the TOI above the dig threshold. Of the 1,244 non-TOI items, 1,013 were correctly labeled.

Of the 1,470 analyzed targets, 29 were "shared" targets, where one item caused multiple EM61-MK2 anomalies selected for MetalMapper analysis. As a result, only 1,441 of the 1,470 cued MetalMapper targets had unique sources. Of the 1,441 unique targets, 428 were identified to be excavated, including 49 training items and 44 targets that could not be reliably analyzed. This resulted in 77 recovered munitions items and 27 recovered ISO items. The remaining 213 items within the "dig" category were non-TOI.

7.3 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

Through retrospective analysis, it is possible to evaluate the true capabilities of a classification procedure based solely on the ranked anomaly list. In a scenario where all geophysical targets may not be intrusively investigated, the success of the procedure will depend on the ability of the analyst to accurately specify the dig/no-dig threshold. The objective was considered met if the threshold could be chosen to achieve the previous two objectives. This amounted to controlling the Type II error (false negative rate) for TOI at zero while also controlling the Type I error (false positives) for Clutter at less than 50%.

All TOI were not retained above the dig threshold. Therefore, the analyst was unable to set a threshold that met this objective.

Based on the Receiver Operating Curve (ROC) curve created from CH2M HILL's prioritized dig list (Figure 7-8), it would not have been possible to choose a threshold that controlled the Type II error (false negatives for TOI) at the specified tolerance (zero) without increasing the Type I errors (false positives for Clutter) beyond the specified tolerance (>50%).

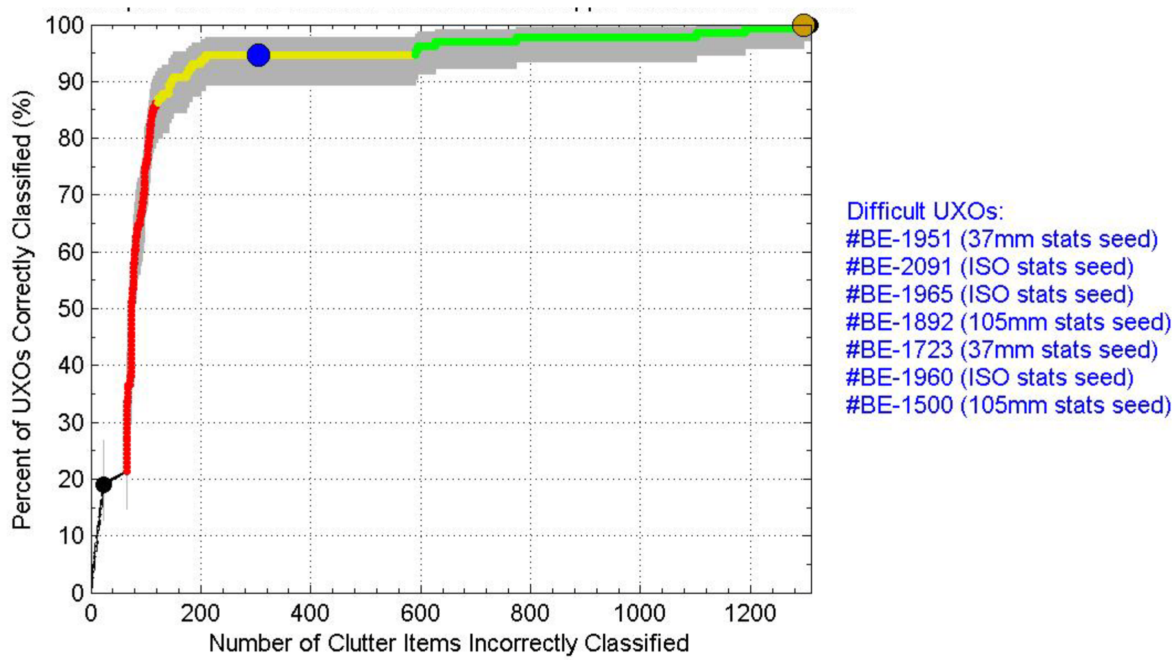


Figure 7-8: ROC Curve for Camp Beale MetalMapper Survey.

In Figure 7-8, the black points at either end of the curve represent hypothetical, extreme choices of the dig threshold. Specifically, the black point at the upper, right end of the curve (just visible under the gold dot) represents the situation where the dig threshold was placed at the very bottom of the ranked anomaly list, such that all anomalies are declared "Dig". Conversely, the black point near the lower, left end of the curve represents the extreme situation in which the dig threshold is placed near the top of the ranked anomaly list, in between the training and calibration data (shown as the solid black portions of the curve), such that only the training data are declared "Dig" while all calibration data are declared "Do Not Dig".

In addition to the black dots, the curve contains two large dots representing two specific dig thresholds. The blue dot represents the stop-dig point chosen by the analyst. The orange dot represents the retrospectively chosen "best case scenario" dig threshold, which would have minimized the false positives for Clutter while ensuring that false negatives for TOI were zero. Listed to the right of the curve are the TOIs that were incorrectly classified (the false negatives) at the analyst's dig threshold (blue dot).

7.4 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

Anomalies for which reliable parameters cannot be estimated using the collected MetalMapper data cannot be classified. These anomalies must be placed in the dig category, which reduces the effectiveness of the classification process.

This objective was to be considered met if reliable parameters were estimated for > 98% of the targets on the prioritized dig list.

Of the 1,441 unique targets, 44 could not be reliably analyzed. This amounts to an estimation rate of 96.9%, which fails to meet the >98% criterion.

7.5 OBJECTIVE: CORRECT ESTIMATION OF TARGET PARAMETERS

This objective involves the accuracy of the target parameters that were estimated in the initial stages of the data analysis. Successful classification was only possible if the modeled features were an accurate representation of the item.

The objective was to be considered met if the estimated X, Y locations were within 15 cm (1σ), and the estimated depths were within 10 cm (1σ) of the true location. Generally, the X, Y location was estimated within 39 cm of the true location. Ground truth information on depths was not made available; nevertheless, this objective is not met on the X, Y criterion alone.

7.6 PERFORMANCE ASSESSMENT SUMMARY

Although the performance objectives of the demonstration were not met, the demonstration provided valuable “hands-on” experience and worked to further the process of transferring the MetalMapper sensor and target classification methods from the researchers and developers to the end-users. The required precision of the survey and the volume of data generated for each surveyed target culminate in a steep learning curve for both the successful collection of the data and its processing and analysis. Nevertheless, this project demonstrated that industry personnel with little to no previous experience with the system can quickly learn to collect data, analyze results, and classify anomalies.

Specific lessons learned in this demonstration include the following:

- It is important to tailor the library of polarizability curves to fit the project site as much as possible. Although unexpected ordnance types are always possible at an unknown site, if certain munitions can be reasonably excluded from the library in advance, a more refined library with fewer individual items may reduce the number of multiple matches to the same type of ordnance. This would allow the analyst to more easily view the fit of the target to multiple ordnance types and to eliminate the easy non-fits.
- Feedback from site-specific excavation results is critical as further training for the classification process.

- Matches to library items must be considered for cases where only one or two of the recovered polarizabilities fit those of a library item.
- The shape of the polarizability curve(s) must be considered even when their amplitudes do not fit a library item (and vice versa).
- TOI may not always exhibit perfect axial symmetry (i.e. the secondary and tertiary polarizability curves may not be perfectly identical).
- Additional demonstration projects and hands-on experience will enable users to improve the ability to collect data, analyze results, and classify anomalies and thereby work to effectively transfer the technology.

8.0 COST ASSESSMENT

ESTCP projects are required to develop and validate, to the extent possible, the expected operational costs of the technology. The intent of this section is to identify the information that was tracked or the data that was obtained during the demonstration that will aid in establishing realistic costs for implementing the technology and comparing it to potential alternative technologies. The tracked costs are provided in Table 8-1 and discussion on the cost elements provided in the following subsections. CH2M HILL was not involved in preparation of the site, so costs are only provided for data collection and data processing. Note that the MetalMapper system and the tractor used to tow the system were provided by ESTCP (through a contract with Geometrics) at no cost to CH2M HILL for this demonstration, thus only daily rates provided by vendors or estimated are provided for those cost elements. The cost per anomaly for data collection also does not include those costs.

Table 8-1: Costs for MetalMapper

Cost Element	Tracked Data	Cost/Quantity
Data Collection Costs		
Pre/Post Survey Activities	Total (does not include estimated costs for components provided by others demarcated by "*")	$6000
	• MetalMapper mobilization (Geometrics fee)*	$1000
	• MetalMapper daily rate*	$500
	• Transportation (ground)*	$2000
	• Tractor mobilization/demobilization*	$500
	• Personnel mobilized	3
	• Personnel mobilization/ demobilization (days)	2
	• Personnel training (days)	1
	• Setup and test pit surveys (days)	1
Survey Costs	Unit cost per anomaly investigated (does not include estimated costs for components provided by others demarcated by "*")	$16.21
	• MetalMapper daily rate*	$500
	• Tractor daily rate*	$200
	• Survey personnel used	3

	• Personnel hours per day	10
	• Daily setup and calibration	1
	• Average number of anomalies surveyed per day (re-surveys are not counted as additional anomalies)	235
	• Estimated additional cost per anomaly for MetalMapper and tractor	$1.50
	• Daily equipment break-down and storage (hours)	0.5
Processing Costs		
Preprocessing (in the field)	Unit cost per anomaly investigated	$4.57
Data processing (office)	Unit cost per anomaly investigated	$6.72

* The MetalMapper system and the tractor used to tow the system were provided by ESTCP at no cost to CH2M HILL for this demonstration, thus these costs are based on estimates or vendor quoted rates.

8.1 DATA COLLECTION COSTS

For the purposes of tracking, the data collection costs were broken out into two sub-categories: (1) Pre/Post Survey and Activities and (2) Survey Costs.

8.1.1 Pre/Post Survey and Activities

CH2M HILL's total cost for the Pre/Post Survey and Activities sub-category includes personnel time for mobilization and demobilization, training with the system (provided by Geometrics personnel), setup and calibration (test pit surveys), and all associated travel costs. Although the MetalMapper used on this project was not paid for from CH2M HILL's project budget, Geometrics was contacted for current rental rates when the cost analysis was performed and the daily cost is provided. The cost to ship the MetalMapper from Geometrics home office to the project site was estimated for this project; however, costs to ship can vary considerably based on distance from the shipping location and the shipping method. Shipping of the MetalMapper by air is a significant cost because some elements of the system (e.g. the sled) cannot be broken down into smaller components.

The tractor used to transport the MetalMapper system around the site was also provided by Geometrics. An estimated daily cost has been provided in Table 8-1; however, this cost will also vary depending on survey locations and available equipment.

8.1.2 Survey Costs

CH2M HILL's survey costs include all personnel hours and associated travel costs for daily setup, system testing, anomaly survey activities, and break-down/storage. Again, the

MetalMapper and tractor used to transport the MetalMapper system around the site was provided by Geometrics. The personnel costs were divided by the number of anomalies on the target list to arrive at the per anomaly cost for surveying. The total number of cued points collected was not used, as re-shots are an expected necessity on most projects. The extra time required for reinvestigation of points with poor data quality was, therefore, factored into the per anomaly cost.

8.2 PROCESSING COSTS

For the purposes of tracking, the processing collection costs were broken out into two sub-categories: (1) Preprocessing and (2) Processing.

8.2.1 Preprocessing

Preprocessing costs included the personnel hours (and associated travel costs since the processing geophysicist was in the field) needed to transform a raw (binary) survey file into a more usable .CSV file, including any background data removal and necessary QC checks. The cost for hardware and software for performing the preprocessing was not included in the costs as these are typically overhead costs. The personnel costs were divided by the number of anomalies on the target list to arrive at the per anomaly cost for preprocessing. The total number of cued points collected was not used, as re-shots are an expected necessity on most projects. The extra time required for reprocessing of points with poor data quality was, therefore, factored into the per anomaly cost.

8.2.2 Processing

Processing costs included the personnel hours to perform all aspects of the data analysis, from import of the individual target .CSV files through compilation of the final ranked dig list. Data processing was performed out of the field and the cost for hardware and software for performing the preprocessing was not included in the costs as these are typically overhead costs. The personnel costs were divided by the number of anomalies on the target list to arrive at the per anomaly cost for processing.

9.0 REFERENCES

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